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A FINITE ELEMENT BASED TECHNIQUE FOR SIMULATING HELIX TWT INTERACTION CIRCUIT THERMAL BEHAVIOR

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13. ABSTRACT (Maximum 200 words)
A technique was developed to assess the thermal performance of a helix Traveling Wave Tube (TWT) interaction circuit accounting for the thermal contact resistance between the circuit's components. This method employed iterative finite element analyses techniques and an analytical expression that related contact pressure to thermal contact resistance. Temperature gradients across the interfaces between the helix and support rods and between the support rods and barrel increase operating temperatures, which can lead to a decline in the tube's performance. Since the circuit analyzed contained no brazes or epoxy at the component interfaces, these thermal drops become more significant.

Parametric runs were made using this methodology for different assembly loads as well as for both beryllia and boron nitride (APBN) support rods. Results showed that the thermal contact resistance effect was more pronounced at lower assembly loads and higher thermal loads. That is, as the thermal loading to the circuit increases, the percent increase of the maximum helix temperature over the helix temperature when the resistance is not accounted for, increases. This effect was also more pronounced when APBN support rods were modeled. The helix temperature increased a greater amount when accounting for the thermal contact resistance for APBN support rods than for BeO support rods.

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0.0 Executive Summary

The effect of Thermal Contact Resistance (TCR) on the thermal performance of an interaction circuit from a helix Traveling Wave Tube (TWT) was examined. This effort was initiated as part of the AFOSR task 2305/F4. The purpose of this effort was to develop fundamental knowledge of how bare contact between interaction circuit components affects the thermal behavior of the interaction region when the TWT is operational. The effect of varying assembly load and different support rod materials were also investigated.

The effect of thermal contact resistance on the thermal performance of electronic devices becomes increasingly important with the absence of brazes or epoxy between contacting components. Thermal Contact Resistance (TCR) is the resistance to heat flow offered by a joint because the area of actual contact is only a fraction of the nominal area [9]. TCR is defined as the ratio of the temperature drop at the interface to the heat flux across the interface. The most accurate method for determining this resistance is to measure it experimentally. However, this requires a sophisticated testing apparatus which may not be readily available to the analyst. If this is the case, analytical techniques must be used to estimate thermal contact resistances.

A method employing finite element analysis and an analytic expression relating contact pressure and material properties to TCR was used to determine the effects of pressure dependent TCR on the thermal performance of a helix TWT's interaction circuit. The method used is based on a method developed by Simon, et al in Reference 12. To begin the procedure, an initial thermal finite element model of the circuit is developed. A three-dimensional, 1/3 symmetric model was constructed of a four turn section of the circuit which represents the circuit's output section. Thin heat conduction elements were introduced at the helix-rod and rod-barrel interfaces of the model to simulate the interfacial thermal contact resistance. This resistance is accounted for by assigning thermal conductivity values to these conduction elements. The temperatures calculated in the thermal analysis were then fed into a corresponding mechanical finite element model. The mechanical model is identical to thermal model except that there were no conduction elements at the component interfaces. The mechanical analysis yielded stresses and deflections for combined assembly and thermal loading. A Fortran 77 program was

written to sort through the resulting output file and calculate the local contact pressures at the material interfaces. The contact pressures, along with the heat flow at the interfaces (calculated in the heat transfer analysis) and material properties were used in an equation relating these parameters to thermal contact resistance to determine the conductance at each interface. These local conductances were then fed back into the thermal input file and another temperature solution was determined using updated thermal conductivities for the heat conduction elements. The entire process was repeated until convergence in the temperature field was achieved.

Parametric runs were made for different assembly loads and support rod materials. Results showed that the thermal contact resistance effect was more pronounced at lower assembly loads and higher thermal loads. That is, as the thermal loading to the circuit increases, the percent increase of the maximum helix temperature over the helix temperature when the resistance is not accounted for, increases. This effect was also more pronounced when boron nitride (APBN) support rods were modeled. The helix temperature increased a greater amount when accounting for the thermal contact resistance for APBN support rods than for BeO support rods.

Finite element based methods such as this can prove to be an important tool in advancing the state of the art of TWT technology by aiding in the design of future TWT components. More accurate assessments could be made for a device's thermal behavior under expected operational and environmental loads which would give tube designers and engineers accurate estimates of a component's useful life.

All work on this project was performed in-house at Rome Laboratory. The finite element analyses were performed on the Electronics Reliability Division's Silicon Graphics 210GTX workstation using NISA, a commercially available finite element code developed by Engineering Mechanics Research Corporation (EMRC).

1.0 Introduction

The thermal characteristics of contacting materials has become increasingly important in a wide range of technologies. When two surfaces are brought into contact, an imperfect junction exists. This holds true whether there is an interstitial medium present (epoxy, solder, thermal grease), or just a bare junction between the two materials. This imperfect junction creates a temperature difference between two contacting surfaces when there is heat flow. Figure 1 illustrates the difference in thermal profiles between a heated bar made up of a homogeneous material and a heated bar consisting of two joined materials. Since the contacting surfaces are not perfectly flat, the heat passes through a finite number of contacting spots, thereby decreasing the heat flow through the joint. Greater contact pressures between the materials generally result in an increased number of contact spots, thereby increasing the flow of heat between the materials. This concept is illustrated in Figure 2. If a fluid is present in the gaps, heat is still conducted across the gap. However, since the thermal conductivities of fluids are orders of magnitude lower than those for metals and ceramics, heat flow becomes more restricted across these gaps, thereby increasing the temperature of the heated material and decreasing the temperature of the unheated material.

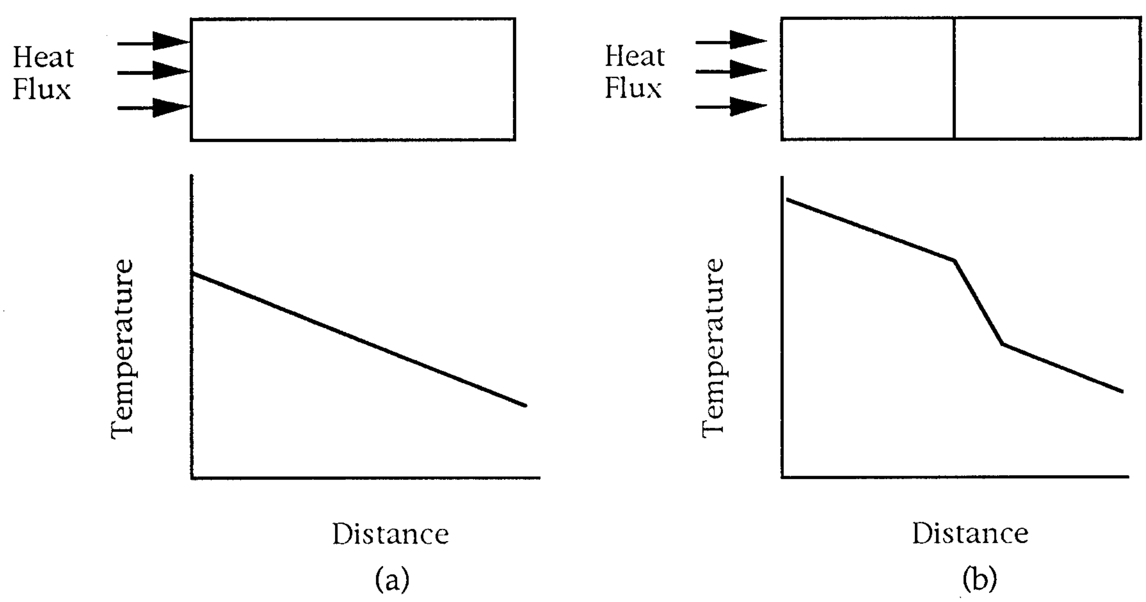

Figure 1: Temperature Variation Along - (a) Homogeneous Bar and (b) Two Joined Bars

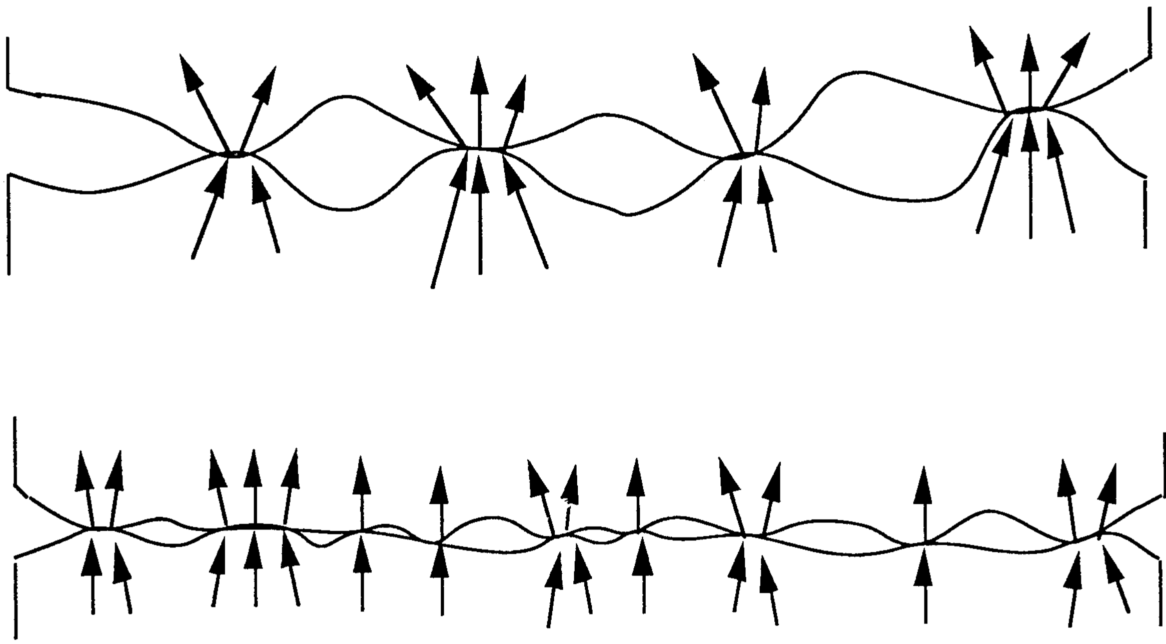

Figure 2: Conduction Heat Flow Through A Joint
Top: Low Contact Pressure
Bottom: High Contact Pressure

The Thermal Contact Resistance (TCR), is defined as the resistance to heat flow across a joint because the actual contact area is only a fraction of the apparent area of the joint. The thermal contact resistance is defined as the ratio of the temperature drop at the interface to the average heat flow across the junction [9]. Heat transfer across the joint may take place by conduction through the actual contact spots, conduction and/or convection through the interstitial medium as well as radiation across the gaps when there is no interstitial material. Thermal contact resistance can play a significant role in determining thermal performance of electronic devices.

The objective of this study was to characterize the effects of contact resistance on the thermal performance of the interaction circuit within a high power helix traveling wave tube. This is of critical importance since failure of the interaction circuit would lead to failure of the entire TWT, of which replacing is essential and costly.

A typical interaction circuit from a helix traveling wave tube (Figure 3) was modeled and used to study the effects of bare contact on thermal performance. The circuit employs a rectangular cross-section helix tape, usually constructed of molybdenum or tungsten. A radio frequency (RF) signal is propagated down the helix at a speed near that of light, however, the axial velocity of the wave is reduced by the pitch of the helix. When an electron beam is injected along the axis of the helix, the axial electric field accelerates some electrons and decelerates others [7]. This causes electrons in the beam to form "bunches" which interact with the helix RF wave, surrendering energy to it. By the time the RF signal reaches the output coupler, it has been amplified exponentially. Dielectric support rods equispaced around the helix act to hold the helix in place and also provide a path by which heat is removed from the helix. In some cases, sections of the rods are coated with a lossy material to dissipate any backward waves reflected back through the circuit from the output waveguide. These rods are usually made of ceramic materials since metallic support rods can not be used to support helices because their negative effect on the RF characteristics on the circuit. The most widely used ceramics are beryllia and APBN. These materials have relatively high thermal conductivities and are well suited for high temperature operation under vacuum. The helix and support rods are enclosed in a vacuum environment by a thin-wall barrel, usually constructed of stainless steel.

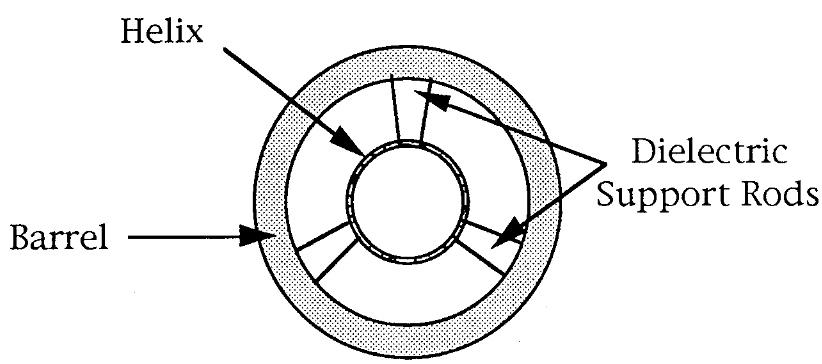

Figure 3: Helix Interaction Circuit Cross-Section

Presently, there are three techniques used for assembling helix/support rod structures. They are [7]:

- Triangulation
- Pressure Insertion
- Brazing

Brazing is the most attractive technique as far as thermal management is concerned. The brazing technique significantly reduces the thermal resistances at the rod interfaces, which reduces the maximum temperature achieved by the helix, thereby allowing the tube engineer a wider choice of helix materials to choose from. Brazing techniques however, are difficult to implement when it comes to helix/support structure assembly. The support rods must be brazed to every turn of the helix and brazing material must be removed from areas between the helix turns. Since this could involve many contact spots (sometimes hundreds), brazing is not always cost effective. Difficulties could also arise from mismatches in thermal expansion coefficient between the brazing material and ceramic. Triangulation and pressure insertion assembly techniques are much easier to implement, but they do not offer the thermal performance characteristics of brazing. The support rod interface resistances are significantly higher since there is only bare contact between the components.

This report discusses a methodology that was developed employing the finite element method to model thermal contact resistances between contacting components within traveling wave tubes. This method was demonstrated on a model of a helix traveling wave tube's interaction circuit. The circuit components are held together under high pressure, there are no brazes or epoxy present within the interaction circuit assembly. Since the contacting surfaces are not perfectly smooth, temperature drops at the interfaces will be more significant when operational heating takes place. Analyses were performed for both beryllia and APBN support rods. The maximum calculated helix temperature were found to be greater for both materials when interfacial contact resistances are accounted for rather than assuming perfectly smooth contact.

This report is organized in the following manner. A brief overview of factors that affect contact conductance heat transfer is first given. These factors include heat flow direction, presence of surface films, presence of interstitial materials and contact pressure. Next, the approach used to model the thermal contact resistances associated with the interaction circuit is described in detail. Finally, results from the simulations are presented and interpreted.

2.0 Overview Of Contact Conductance Heat Transfer

Heat flow through a homogenous solid is greater than the heat flow through an interface between contacting solids with similar material thermal conductivities. This is caused by the inherent roughness of the contacting surfaces which prevents the solids from making perfect contact. Heat is actually conducted through a finite number of contacting spots within the apparent contact area. The interfacial contact resistance between contacting materials is dependent upon a number of factors. These factors include:

- Direction Of Heat Flow
- Presence Of Surface Films
- Presence Of Interstitial Medium
- Contact Pressure

2.1 Effect Of Heat Flow Direction

The effect that the heat flow direction has on the contact conductance (inverse of TCR) is known as thermal rectification. This phenomena occurs when the thermal contact conductance of a junction composed of dissimilar materials varies with the direction of heat flow. Thermal rectification occurs when heat flows between dissimilar materials because of the difference in the deformations of the contacting surfaces. Since dissimilar materials deform differently, the actual contact area between the materials can increase or decrease, depending on the direction of heat flow, when heating occurs. The following observations have been made regarding the effect of thermal rectification on contact conductance heat transfer [9].

1. For surfaces initially convex, the conductance through the joint is higher when the heat flows from the material with the higher α/k ratio (Coefficient of thermal expansion/thermal conductivity). This is also generally true for flat-smooth surfaces.

2. For flat-rough surfaces, the conductance through the joint is higher when the heat flows from the material with the lower α/k ratio.

3. Similar materials with dissimilar surfaces may exhibit the rectification effect.

4. The rectification effect generally decreases as the number of reversals increases.

2.2 Effect Of Surface Films

Surface films may exist in the form of electroplated surfaces (intentional) or oxidized surfaces (unintentional). Studies on the effect of surface films on contact conductance heat transfer have shown the following [9].

1. For flat-rough surfaces, coatings of higher conductivity metals a few tens of microns thick will noticeably reduce the TCR.

2. Oxide films do not appreciably increase the TCR unless the film is sufficiently thick.

2.3 Effect Of Interstitial Materials

Heat transfer through voids filled with a gas occurs principally by conduction. The heat transfer coefficient for the gas gap is given by $h_g=k_g/\delta$ where k_g is the thermal conductivity of the gas and δ is the effective thickness of the gas gap. The effective gap thickness is similar in magnitude to the mean free path of the gas molecules. Experiments have found that the gas conductance is more dependent on the molecular mass of the gas than the gas thermal conductivity. Under certain conditions, the gas conductance of Xenon has shown to be greater than that of Helium even though the thermal conductivity of Helium is 30x greater than that of Xenon.

Gaps between contacting surfaces can also be filled with materials to either increase or decrease TCR to provide a means of thermal control. Some common interstitial materials include metal foils, wire screens, thermal greases or insulating sheets, depending on the application. Indium foil and Silicon grease have been found to be suitable materials to enhance contact heat transfer [9]. The presence of

conducting fluids has also been found to greatly reduce TCR, thereby increasing contact heat transfer.

2.4 Effect Of Contact Pressure

Experiments have shown [3] that thermal contact resistance is directly dependent on contact pressure at the material interface. When two surfaces are pressed together, contact is made at a finite number of discrete points (see Figure 2). Increases in contact pressure increase the local deformation at the interface between the two materials, thus increasing the size and number of contact points. This, in turn would cause a lower the TCR between the contacting materials, thus increasing heat flow. Conversely, lower contact pressures tend to increase the TCR at the material interface, thus decreasing heat flow.

3.0 Approach

Because there is an interference (pressure) fit in the interaction circuit assembly, without films or interstitial materials, only pressure dependence was examined for it's effect on TCR. The flow of heat through the circuit follows one path only (helix-rod-barrel), therefore, it was not necessary to examine the effect of the reversal of heat flow direction on the circuit's thermal performance. An iterative method employing finite element analysis and an analytic expression relating contact pressure to TCR was used to determine the effects of pressure dependent TCR on the thermal performance of a helix TWT's interaction circuit. The method used is based on a method developed by Simon, et al in Reference 12. It provides for iterative coupling between thermal and mechanical finite element models.

To begin the procedure, an initial thermal finite element model is developed. A one-third model of a typical helix TWT interaction circuit is shown in Figure 4. The support rods are positioned at equal 60 degree intervals around the helix, providing for one-third symmetry. Only a four turn section of the circuit was modeled, representing the circuit's output section. Heat dissipation was simulated on the inside diameter of the helix elements and a boundary temperature of 100 degrees C was assigned to all nodes on the outer surface of the barrel. Relatively thin heat conduction elements were introduced at the helix-rod and rod-barrel interfaces of the model to simulate the interfacial TCR. The TCR is accounted for by assigning thermal conductivity values to these conduction elements. In the initial heat transfer run, these interface elements were assigned artificially high thermal conductivity values. The reason for doing this was to simulate zero thermal resistance at the interface. In subsequent iterations, these conductivities would be adjusted to account for the thermal resistance.

The temperatures calculated in the thermal analysis were then used as a loading condition into a mechanical finite element model. This mechanical finite element model is identical to the thermal finite element model except that there are no thin conduction elements at the material interfaces. The boundary conditions for the mechanical finite element model are shown in Figure 6. The mechanical analysis yields stresses and deflections for combined assembly and thermal loading. A Fortran 77 program was written to sort through the resulting output file and

Helix TWT Interaction Circuit
1/3 Finite Element Model

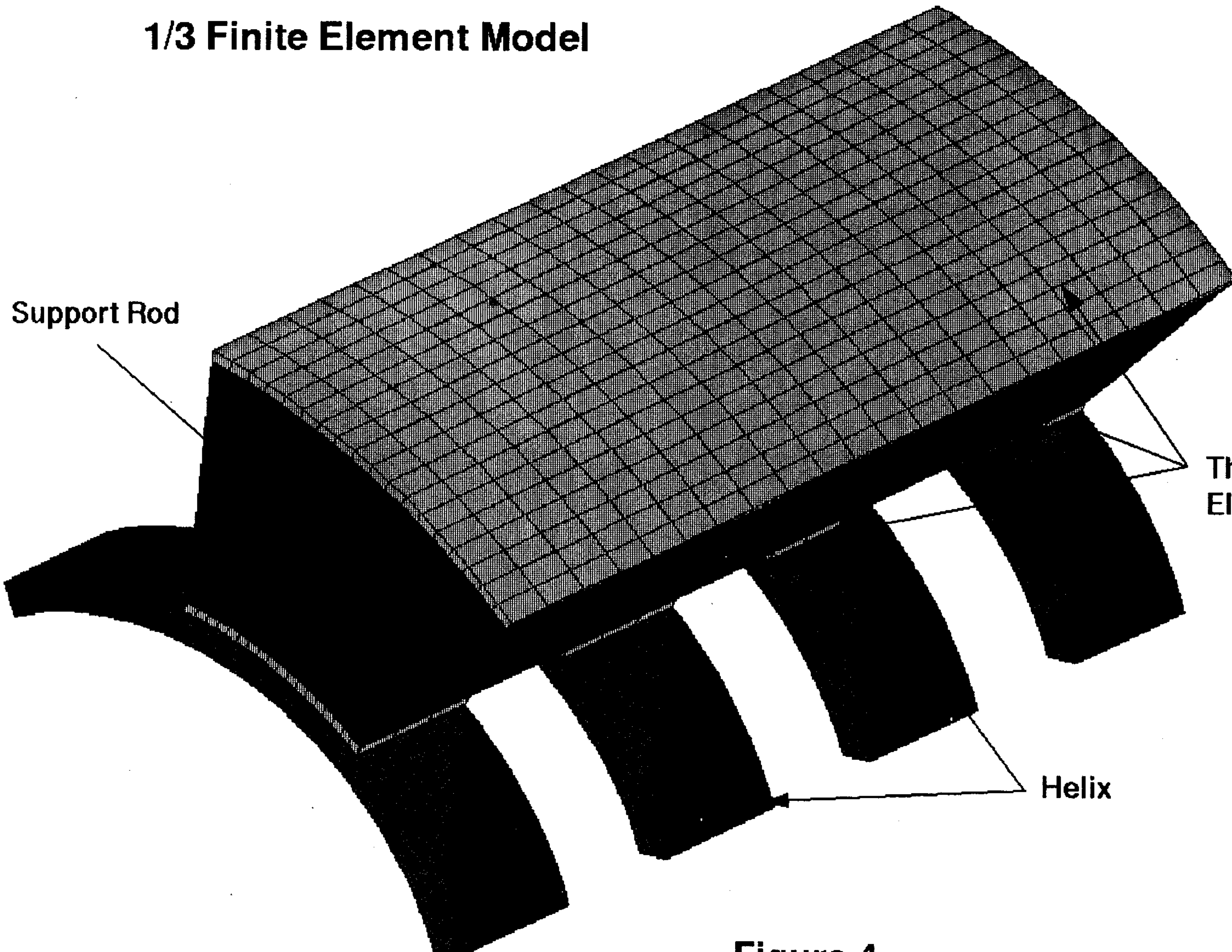

Figure 4

calculate the local contact pressures at the material interfaces. The contact pressures, along with the heat flow at the interfaces (calculated in the heat transfer analysis) and material properties were used in an equation relating these parameters to TCR to determine the conductance at each interface (see Appendix A). These local conductances were then fed back into the thermal input file and another temperature solution was determined using updated thermal conductivities for the heat conduction elements. The entire process was repeated until convergence in the temperature field was achieved. A flowchart outlining this process is shown in Figure 5.

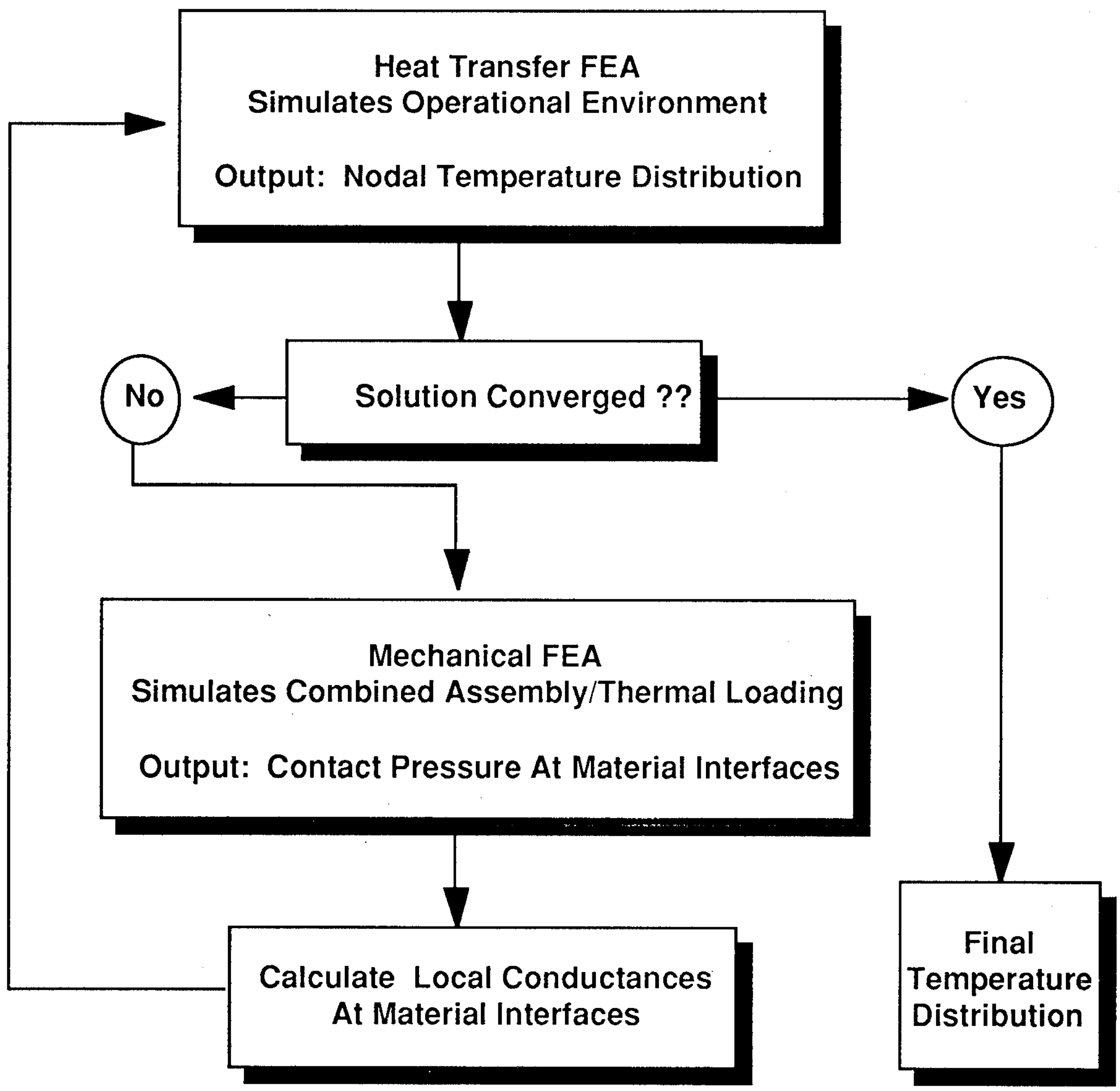

Figure 5: Methodology Flowchart

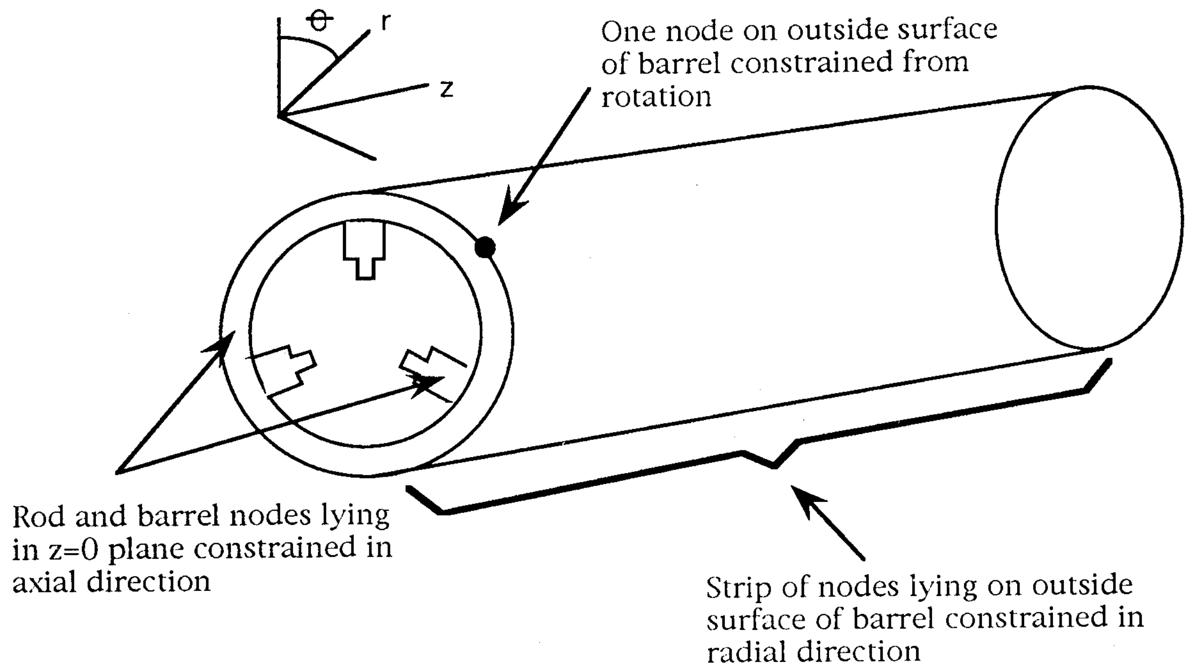

Figure 6: Mechanical Finite Element Model Boundary Conditions

4.0 Results

Parametric runs were made to determine the effects of certain parameters on the thermal performance of the interaction circuit. The following analyses were made using this methodology:

Assembly Load	Rod Material	Heat Input (W/turn)
100 ksi	Beryllia	5
		7
		10
		15
200 ksi	Beryllia	5
		7
		10
		15
200 ksi	APBN	5
		7
		10
		15

Temperature contours are shown in Figures 7 & 8. This case is for an assembly load of 200 ksi, beryllia support rods, and 10 Watts per turn heat dissipation. Figure 7 shows the temperature distribution when the TCR is not accounted for. That is, heat is assumed to flow between components with no resistance. Figure 8 shows the results using the TCR analysis method. The charts that follow show the results for all cases analyzed. The maximum temperature attained by the helix (Degrees C) represents the hottest point within the circuit during operation.

Interaction Circuit Thermal Contours Without TCR Accounting

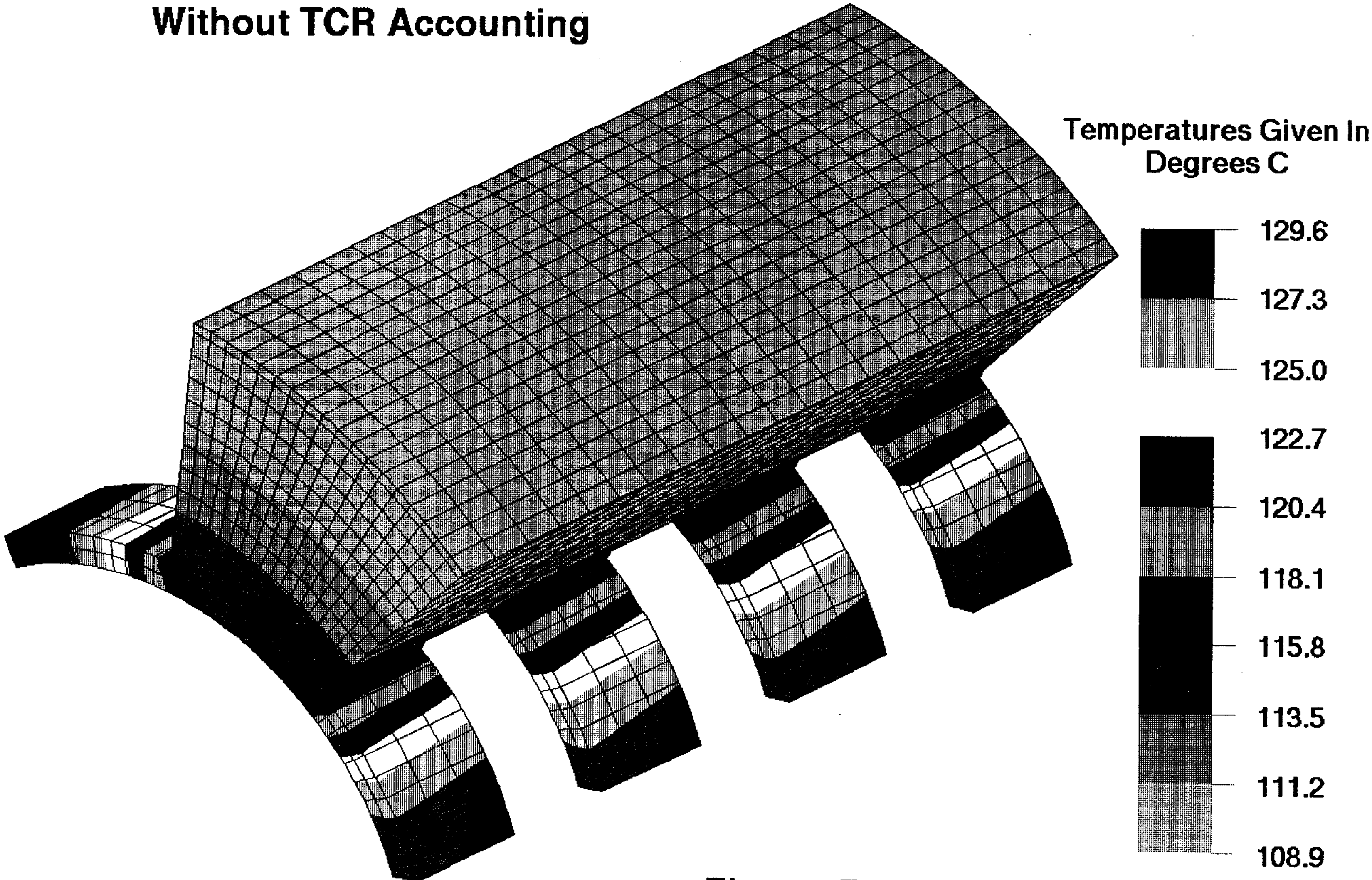

Figure 7

Interaction Circuit Thermal Contours With TCR Accounting

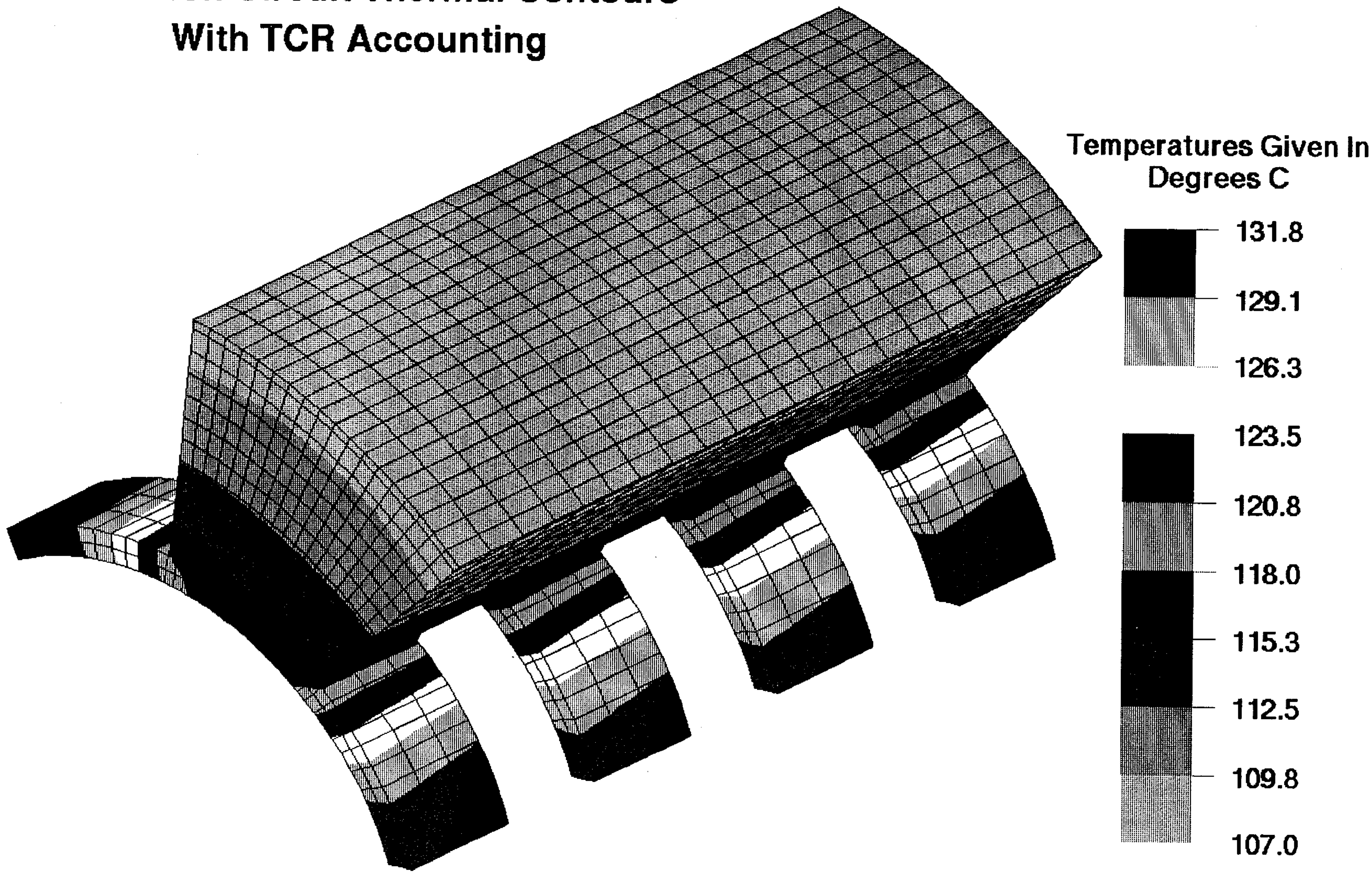

Figure 8

Assembly Load: 100 ksi
Rod Material: BeO

Heat Input (W/Helix Turn)	Max. Helix Temp. (Without TCR Accounting)	Max. Helix Temp. (With TCR Accounting)	% Difference In Max. Helix Temp.
5	114.7	115.8	.95
7	120.6	122.4	1.47
10	129.6	132.5	2.19
15	144.8	148.5	2.49

Assembly Load: 200 ksi
Rod Material: BeO

Heat Input (W/Helix Turn)	Max. Helix Temp. (Without TCR Accounting)	Max. Helix Temp. (With TCR Accounting)	% Difference In Max. Helix Temp.
5	114.7	115.8	.95
7	120.6	122.2	1.31
10	129.6	131.8	1.67
15	144.8	148.1	2.23

Assembly Load: 200 ksi
Rod Material: APBN

Heat Input (W/Helix Turn)	Max. Helix Temp. (Without TCR Accounting)	Max. Helix Temp. (With TCR Accounting)	% Difference In Max. Helix Temp.
5	121.8	123.4	1.30
7	130.7	132.8	1.58
10	143.8	147.1	2.24
15	166.0	170.8	2.81

These results show that the effect of TCR on the thermal performance of this structure becomes more pronounced with lower assembly loads. This is no surprise since lower contact pressures effectively decrease the number of contact spots at the material interfaces, thus decreasing heat flow between the materials and, in this case, increasing the maximum helix temperature.

The TCR also becomes more significant at higher thermal loads. The results show that the percent difference in the maximum helix temperature increases when the heat input to the system increases, regardless of assembly load. The reason for this is that the equation used to calculate the TCR indicates that thermal loading is directly proportional to the TCR at the material interfaces (see Appendix A). Therefore, an increase in the interfacial TCR brings with it an increase in the helix temperature.

The support rod material also was found to have an effect on the thermal performance of this interaction circuit when thermal contact resistance is accounted for. For the same assembly load, the maximum helix temperature ranged from 6-13 % higher for APBN support rods than for BeO support rods. This demonstrates that this method can play an important role in the material selection process when designing microwave tube components. It allows similar types of materials as well as materials of different classes to be analyzed and evaluated for proposed helix interaction circuit designs.

5.0 Conclusions

Use of the finite element based TCR accounting methodology developed in this study provides the means for helix TWT designers and engineers to more accurately predict thermal instabilities within helix interaction circuits. The phenomena of interfacial thermal contact resistance should not be neglected when characterizing the thermal behavior of helix interaction circuit designs. This especially holds true when the pressure insertion technique is used to assemble the circuit. When brazing or epoxy is used, the TCR effect is less pronounced but still present. The following conclusions were made in demonstrating the TCR accounting method on a typical helix TWT interaction circuit model:

- Lower assembly loads increase the TCR effect thus increasing the maximum temperature attained by the helix for a given heat dissipation.

- Higher thermal loading tends to increase the TCR effect. The increase in helix temperature over the temperature when the TCR is not accounted for was found to increase when the heat load applied to the circuit was increased.

- Although support rod materials are generally limited to ceramics, the choice of support rod material can significantly affect the thermal performance of interaction circuit designs. The circuit temperatures when APBN rods were modeled were found to be greater than the temperatures when BeO rods were modeled.

The TCR accounting method was demonstrated on an interaction circuit model that contained commonly used materials, typical dimensions and an arbitrary geometry for the support rods. Similar types of materials as well as materials of different classes can be analyzed and evaluated for proposed helix interaction circuit designs using this method. This method could also be applied to different component geometries provided the proper geometric properties are known. Finite element based methods such as this have great potential to aid in future helix TWT development and upgrade efforts.

Appendix A
Derivation of Thermal Contact Resistance Equation

This equation is given by Barber in Reference 3. It was assumed that all deformation is elastic and that the solids are in perfect contact throughout the elastic contact area.

The heat flow per unit area through single circular areas of two contacting solids is given by:

$$q = \frac{K_o(T_1 - T_2)}{\pi\sqrt{a^2 - r^2}} \qquad (1)$$

Where: K_O ~ Equivalent Thermal Conductivity of Contacting Solids

$$K_o = \frac{2K_1K_2}{(K_1 + K_2)}$$

T_1,T_2 ~ Temperature of Solids 1 & 2, Respectively

a ~ Radius of Contact Area

r ~ Distance From Axis of Symmetry

The total heat flow rate (Q) through the contact area is obtained by integrating Eq (1).

$$Q = 2K_o(T_1 - T_2)a \qquad (2)$$

Next, a pressure distribution necessary to make the thermally distorted solids conform throughout the contact area must be found. By approximating the equation of a distorted surface as a paraboloid, this pressure distribution (p) is given by:

$$p = \frac{4}{\pi c_o}\left[\frac{1}{2R_o} + \frac{(c_2 - c_1)(T_1 - T_2)K_o(1 - \log 2)}{\pi a}\right]\sqrt{a^2 - s^2} \qquad (3)$$

Where: $$c_{1,2} = \frac{(1-\upsilon_{1,2}^2)}{E_{1,2}}$$

$\upsilon_{1,2}$ ~ Poisson's Ratio of Solids 1 &2, Respectively

$E_{1,2}$ ~ Elastic Modulus of Solids 1 & 2, Respectively

$$c_o = \frac{(1-\upsilon_1^2)}{E_1} + \frac{(1-\upsilon_2^2)}{E_2}$$

$$R_o = \frac{R_1 R_2}{(R_1 + R_2)}$$

$R_{1,2}$ ~ Radii of Curvature of the Contacting Surfaces When Unheated

s ~ Distance From Axis of Symmetry

The total load is obtained by integrating equation (3) over the contact area.

$$W = \frac{4a^3}{3R_o C_o} + \frac{8(c_2 - c_1)(T_1 - T_2)K_o(1-\log 2)a^2}{3\pi c_o} \quad (4)$$

The Thermal Contact Resistance (ρ) is defined as the temperature difference (T_1-T_2) per unit heat flow (Q).

$$\rho = \frac{(T_1 - T_2)}{Q} \quad (5)$$

Substituting Equation (2) for Q gives:

$$\rho = \frac{1}{2} K_o a \quad (6)$$

Finally, combining Equations (2), (4) and (6):

$$\frac{2(1-\log 2)(c_2 - c_1)Q}{\pi} + \frac{1}{2R_o K_o{}^2 \rho^2} = 3c_o W K_o \rho \quad (7)$$

Equation (7) is the thermal contact resistance equation. It is solved iteratively for ρ. K_o, $c_{1,2}$ and R_o are known quantities while Q and W are determined from the thermal and mechanical finite element analyses.

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Mission. The mission of Rome Laboratory is to advance the science and technologies of command, control, communications and intelligence and to transition them into systems to meet customer needs. To achieve this, Rome Lab:

a. Conducts vigorous research, development and test programs in all applicable technologies;

b. Transitions technology to current and future systems to improve operational capability, readiness, and supportability;

c. Provides a full range of technical support to Air Force Materiel Command product centers and other Air Force organizations;

d. Promotes transfer of technology to the private sector;

e. Maintains leading edge technological expertise in the areas of surveillance, communications, command and control, intelligence, reliability science, electro-magnetic technology, photonics, signal processing, and computational science.

The thrust areas of technical competence include: Surveillance, Communications, Command and Control, Intelligence, Signal Processing, Computer Science and Technology, Electromagnetic Technology, Photonics and Reliability Sciences.